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Temperature Dependence of Dynamic Deformation in FCC Metals, Aluminum and Invar

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Abstract. Laser-driven shock experiments were performed on fcc metals, aluminum and invar, at a range of initial temperatures from approximately 120-800 K to explore the effect of initial temperature on dynamic strength properties at strain rates reaching up to 10^7 s^{-1}. In aluminum, velocimetry data demonstrated an increase of peak stress of the elastic wave, σ_E, with initial temperature. Alternatively, for invar, σ_E exhibits little-to-no decrease over the same initial temperature range. Aluminum's unusual deformation behavior is found to primarily be due to anharmonic vibrational effects. Differences in the magnetic structure of aluminum and invar can account for discrepancies in high rate deformation behavior.

Introduction

The study of high rate material deformation is of fundamental importance in material science and condensed matter physics. This paper presents work on aluminum and invar ($Fe_{64}Ni_{36}$) to investigate dynamic strength behavior of two fcc metals. Under high strain rate loading, the flow stress of a material will increase immoderately with strain rate [1, 2, 3, 4, 5, 6, 7] and in shock loading, σ_E will also dramatically increase [8]. This transition will usually start at strain rates 10^3-10^6 s^{-1}, depending on the material. Often, this trend is associated with *phonon drag*, although the term phonon drag is already attributed to a separate phonemonon in solid state physics, so to avoid confusion it is better to classify it as an effect associated with nonlinear elastic behavior. For some fcc metals loaded under high strain rates, including aluminum, there is an increase in σ_E with increasing temperature [9, 10, 11]. Previous work has studied temperature dependence at high strain rates in numerous materials and has shown the marked, anomalous rise of σ_E is seen in aluminum and noticeably in tin, copper, and silver, while other metals demonstrate varied temperature-dependent behavior [12, 13, 11, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25].

The relaxation behavior of the elastic wave is inextricably tied to the plastic deformation front behind it. Clifton and Markenscoff described the decay of the elastic shock as it propagates through a material as the interaction of the compressive elastic shock front with the elastic relaxation waves emitted from moving dislocations [26, 27, 28]. This is important to understand when accounting for trends in the σ_E across materials.

Experimental Methods

Laser-driven shock experiments were performed at the high powered laser-system at the Trident Laser Facility in Los Alamos National Laboratory. The drive beam operated at 527 nm for a duration of 5 ns delivering a 5 mm diameter spot. For both aluminum and invar, drive energy was approximately 100 J. The primary diagnostic was a pair of line-imaging velocity interferometers (VISARs) which enabled measurement of free surface velocity at the rear of the target [29].

The target holder was designed to pre-cool targets to temperatures as low as 80 K and pre-heat as high as 800 K. Steel tubing connected ran through the target holder around the target on the inside of the chamber. Liquid nitrogen

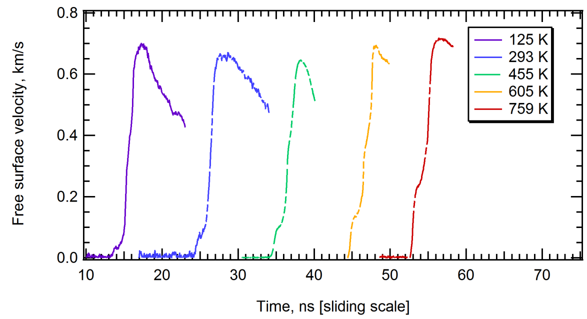

FIGURE 1. Particle velocity off the rear surface of aluminum as a function of temperature under dynamic loading conditions approaching 10^7 s^{-1}. There is a general trend of increasing σ_E as temperature increases.

was poured in through one end of the tubing outside the chamber, thereby cooling the target holder and the target. The parts between the target and the tubing were all copper to ensure good thermal conductivity. Two 120 V heater cartridges, each 3 mm in diameter and approximately 3 cm long, were inserted into the aluminium body of the target holder on opposites sides of the target and would resistively heat according an applied voltage which was regulated by a PID temperature controller linked to a thermocouple. The thermocouple was placed between the copper washer holding the target and the copper fixture on the target holder. In addition to providing feedback for the PID controller while the target reached the desired temperature, it was used to determine the temperature of the target just before the shot.

For aluminum, strain rates ranged from $10^6 - 10^7$ s^{-1} in order to compare temperature dependence as a function of strain rate. For invar, strain rates were around 10^6 s^{-1}. Loading of all aluminum and invar samples was performed under similar loading conditions. Samples were punched out from 125 micron foils purchased from Goodfellow, Cambridge Limited. The aluminum was annealed and of 99.0% purity. The aluminum samples had a grain size of 10-50 microns, the invar samples had a grain size of 5-10 microns. The targets were 12 mm in diameter and 125 microns thick.

Results

Velocimetry data for aluminum shocked at strain rates around 10^6 and 10^7 s^{-1}, the latter is shown in Figure 1. It can be seen that the amplitude of the elastic precursor wave increases with temperature. σ_E can be inferred from the peak velocity in the elastic wave by the Hugoniot jump conditions, such that

$$\sigma_E = \frac{1}{2}\rho c_L u_p \tag{1}$$

where ρ is initial density, c_L is longitudinal sound speed and u_p is the particle velocity at the peak of the elastic wave. Therefore, σ_E is approximately proportional to u_p. Exact values with error bars can be seen in work by Chen et al. [30]. Invar was loaded at a strain rate around 10^6 s^{-1}. Figure 2 shows the line-outs as a function of temperature for invar. There appears to be little-to-no decrease in σ_E as temperature increases.

Discussion

Invar does not appear to have the same temperature-dependent behavior as seen in fcc materials at high strain rates. Invar is set apart from other metals in its exceptionally low thermal expansion properties around atmospheric temperatures and pressures. As thermal expansion arises from the anharmonic terms of ionic interaction energy [31, 32], it implies that contributions from these terms are suppressed in invar. The suppression of anharmonicity in invar metals is substantiated by studies of the phonon density of states across temperature, which show that there is little to no softening of the phonon modes as temperature increases [33, 34]. It is has been determined that this property arises from the abilty of invar to relax its magnetic structure by continuously transitioning between collinear (triplet/ferromagnetic) and noncollinear (singlet/non-ferromagnetic) configurations. This transition is facilitated by the small magnitude of

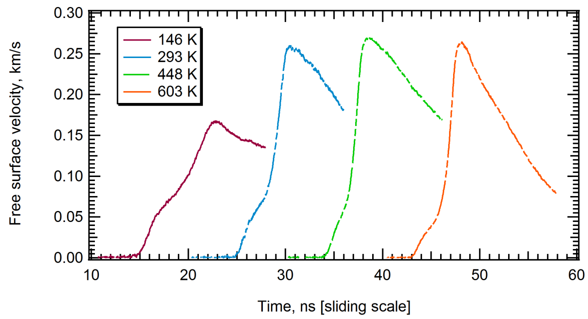

FIGURE 2. Particle velocity off the rear surface of invar as a function of temperature loaded under strain rates exceeding 10^6 s^{-1}. There is a modest trend of σ_E decreasing as temperature increases.

the ΔE associated with the difference in energies of the two spin states, and that this mechanism allows invar to suppress anharmonic scattering effects [35, 36, 37]. Thus, the ability of a material to relax its magnetic structure can be a strong indicator of a material's capacity to suppress anharmonicity.

That invar can suppress phonon anharmonicity is relevant to how it is affected by dislocation drag because both phonon-dislocation scattering and thermoelastic damping are products of anharmonicity [38, 39, 40]. In addition, increased anharmonicity results in a lower acoustic wave group velocity, thus inhibiting the elastic waves, including the elastic relaxation waves which are emitted from the dislocations. This effect is exacerbated under extreme conditions, such as high temperature and/or high rate loading, in which the phonon mean free path (MFP) will decrease. This decrease in MFP results in increased anharmonic phonon scattering. Umklapp processes will also increase with increased scattering, and will dissipate entropy [31, 32]. Thus, drag on both the dislocations and the elastic waves is a consequence of anharmoncity.

The Gruneisen parameter can be used as a measure of anharmonicity. It appears in calculations of phonon-dislocation scattering and thermoelastic damping [38, 41, 39, 42]. The Gruneisen parameter is defined as

$$\gamma_k = -\frac{V}{\omega(k)}\frac{\partial\omega(k)}{\partial V} \tag{2}$$

in which $\omega(k)$ is the phonon frequency as a function of the wavevector, k, and V is volume. One can see that as a the ionic energy terms approach the harmonic approximation, the Gruneisen parameter approach zero. Thus, a low Gruneisen parameter indicates the material behaves in a way that tends toward the harmonic lattice approximation, and conversely, a higher Gruneisen parameter indicates increased anharmonicity in the lattice. While this form makes it clear to see the Gruneisen parameter as a measure of anharmonicity, it can be derived into a more convenient form from the bulk thermodynamic properties of a material as

$$\Gamma = \frac{\alpha K}{c_v \rho} \tag{3}$$

where α is thermal expansion coefficient, K is bulk modulus, c_v is specific heat capacity, and ρ is density. This can be calculated for various materials for comparison of nonlinear elastic behavior which results from anharmonic phonon interactions. Additionally, experimental data which uses neutron scattering to probe the phonon density of states can be used to quantify the increased anharmonic contributions in materials with higher Gruneisen parameters. A comparison of the phonon density of states between aluminum and invar shows that while invar has little to no softening of the phonon modes with increasing temperature [33, 34], aluminum has appreciable softening [43], demonstrative of increased anharmonic contributions. Further comparison of fcc metals can be done by comparing the nickel phonon density of states to aluminum and invar. Nickel has a Gruneisen parameter between that of aluminum and invar and exhibits moderate softening across with increasing temperature [44]. Thus, the "phonon drag" force that attenuates the elastic shock can be attributed in large part to nonlinear elastic effects arising from anharmonic phonon scattering. This would not only delay the arrival of the both the elastic and plastic shock waves, but it would also suppress elastic relaxation waves emitted from the dislocations through the compressed material, preventing them from lowering the σ_E.

That invar can suppress anharmonicity by manipulating its magnetic structure suggests that it may be possible to correlate the magnetic or electronic structure of other materials to the ability to suppress anharmonicity and consequently subdue phonon scattering effects. It is perhaps a better system of categorization to infer a material's inclination for nonlinear elastic behavior by its electronic band structure or its grouping on the periodic table than by its crystal lattice structure. Nonetheless, band structure and lattice structure are inextricably related properties, so it is likely that trends in properties dependent on nonlinear elastic effects between materials of identical lattice structures will still hold.

Conclusions

Fcc metals, aluminum and invar, were dynamically loaded using a high-powered laser system paired with a heating/cooling system to study the effect of temperature on the dynamic strength of metals. Experimental results showed that in aluminum, σ_E will increase with temperature, in contrast to invar which has little-to-no decrease in σ_E with increasing temperature. This difference is attributed to the differences in electronic and magnetic structure between the two metals. Invar can relax its magnetic structure to suppress anharmonicity from the phonon modes, thereby subduing nonlinear elastic effects. That aluminum does not have such a capability results in behavior more strongly influenced by nonlinear elastic effects.

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